

Examining the life-cycle environmental impacts of desalination: A case study in the State of Qatar

Mehzabeen Mannan^a, Mohamed Alhaj^a, Abdel Nasser Mabrouk^{a,b}, Sami G. Al-Ghamdi^{a,*}

^a Division of Sustainable Development, College of Science and Engineering, Hamad Bin Khalifa University, Doha, Qatar

^b Qatar Environment and Energy Research Institute, Hamad Bin Khalifa University, Doha, Qatar

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ABSTRACT

Comprehensive environmental impact of thermal desalination is poorly understood in Middle Eastern and North African region, especially for multistage flash (MSF) desalination. Nearly 75% of Qatar's municipal water supply is being produced by MSF due to process reliability and other advantages, which is highly energy-intensive and creates an enormous environmental burden. Hence, this paper aimed to develop a multi-faceted, life-cycle based framework that quantifies the overall environmental and human health impacts of MSF desalination in Qatar. Three different MSF systems were examined by varying the gain ratio (GOR) through life cycle assessment. Different environmental loads were examined and evaluated, including climate change, freshwater eutrophication, fossil fuel depletion, ozone depletion, and human toxicity. The results showed that the modified MSF configuration with higher GOR released 7.32 kg CO₂ for 1 m³ of water production while the plant with lowest GOR released 12.6 kg. Quantitative analysis of the environmental degradation caused by desalination reflects the reality of water use in Qatar and can motivate users to reduce their water consumption as part of the Qatar's national vision 2030. The implication of this study is particularly important at a regional level as it serves as a preliminary baseline for a more efficient water strategy.

1. Introduction and background

The freshwater crisis is one of the challenges restricting global sustainable development and is mainly attributed to rapid population and economic growth, and a lack of proper development in the water management sector. Desalination, a non-conventional source of potable water, has become a feasible solution to the water shortage problem for many communities worldwide, securing the future of humanity. It is the only viable source of water in Gulf Cooperation Council (GCC) countries where water is a rare commodity. Being a GCC country, Qatar has one of the largest desalination capacities in the world. Almost 99% of municipal water in Qatar is desalinated water (DW) [1].

Compared to the other well-established global water treatment processes, seawater desalination is the most energy intensive technology, most importantly the thermal desalination [2]. Although desalination techniques offer many social, economic, and public health benefits, their highly energy-intensive nature create significant environmental impacts. Air pollution associated with fossil fuel use and coastal water quality degradation due to the discharge of highly saline brine are negative environmental impacts. As Qatar is highly dependent on desalination technique for fresh water, a comprehensive

quantification of the environmental impacts is necessary to allow us to identify means to increase the environmental sustainability of the process. Such assessment will assist decision makers regarding future trends in the desalination market from an environmental viewpoint.

1.1. Qatar water security & desalination

In the State of Qatar, Rainfall (80 mm avg. per year) and groundwater are the only freshwater resources in Qatar, and underground water is extensively abstracted in agricultural activities. The annual per-capita renewable water resources (rainfall and groundwater) in Qatar are 71 m³, while 1000 m³/yca is considered as the minimum required sustaining life [1].

Owing to geographical limitations and the substantial increase in population over the last few decades (Fig. 1), seawater desalination has received focus to make it the sole supply of potable water and maintain sustainable development. According to the water desalination statistics of 2015, approximately 493 million m³ of desalted water was produced in 2014 [4]. In this water scenario, Qatar has one of the highest water consumption rates per capita of almost 500 L/day [5]. QNDS (Qatar National Development Strategy) estimated that, by 2020, water

* Corresponding author.

E-mail address: salghamdi@hbku.edu.qa (S.G. Al-Ghamdi).

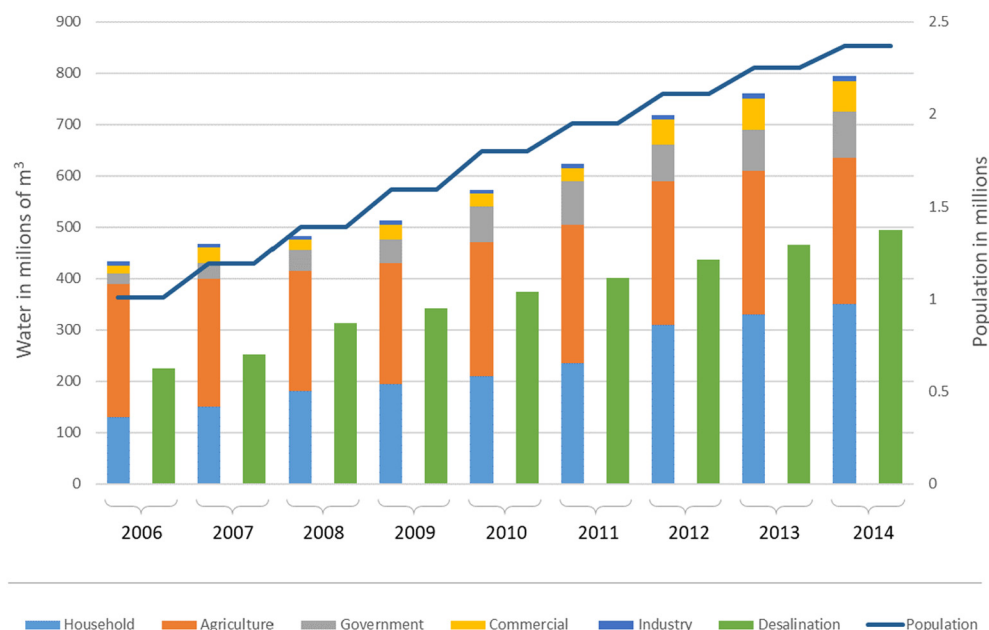


Fig. 1. Growth in water production through desalination and water use in different economic sector with population increase during 2006–2014. The water uses almost doubled in these 8 years period and most of the water has been allocated for household and agricultural purpose. The economic sectors have been indicated using different colors and the water that is being used is originating from three sources: seawater desalination (59%), groundwater abstraction (30%), and treated sewage effluent (11%) [4].

consumption will increase by almost 5.4% for Qatari people, or by 7% for expats in Qatar [6,7]. Hence, the rise in population and water consumption, together with the continuous shortage of natural potable water, will rapidly increase the number of desalination plants in Qatar in the near future.

Seawater can be desalted using either thermal or membrane processes. In Qatar, three desalination processes are commonly used: (a) multi-stage flash distillation (MSF), (b) multi-effect distillation (MED), and (c) reverse osmosis (RO). Among these three technologies, MSF is widely used, supplying 75% of Qatar's total desalinated water. However, worldwide, RO is the leading technology due to its lower energy consumption and production costs, but this technology has not yet been proven to be more suitable than MSF in Qatar. The reasons for this are mainly the process reliability of MSF plants, the ability to treat seawater with: high salinity, low quality, high turbidity, and high temperature, minimal pre and post treatment for red tides compared to RO, and a lack of sufficient experience in other technologies [8,9]. Moreover, installing and maintaining MSF plants is less complicated than other technologies. All these site-specific conditions validate the future use of MSF technology over a long term with further expansion in the State of Qatar. The current production capacity of all desalination plants in Qatar with specifications is listed in Table 1.

1.2. Life cycle assessment in desalination

Over the last two decades, several studies have assessed different aspects of desalination, and some concentrated on the impacts of desalination on the environment and human life. Both qualitative and quantitative examinations were conducted to assess the impacts of different types of desalination. In the qualitative assessment studies, the impacts generated from atmospheric emissions, discharge of heated effluents and chemicals into the marine environment, impacts of noise, effects on land use, and impacts on aquifers were discussed and explained without considering life cycle assessment (LCA). Hopner T. et al. [47], Morton A. et al., Medeazza M. V., Sadhwani J.J. et al., Hashim A. et al., Lattemann S. et al., and Mezher T. et al. and others qualitatively analyzed the effects of desalination in their respective studies [11–18].

Research focusing on the LCA of desalination to evaluate its environmental impacts began in 1990 [19]. Three different desalination techniques, combined with different energy production technologies,

Table 1

Current and future production capacity of desalination plants in Qatar with general descriptions [1,6,10].

Desalination plants	Capacity (MIGD)	Technology	Commissioning	Specification
Current production				
Ras Abu Fontas A	55	MSF	1980	Brine recirculation
Ras Abu Fontas A1	45	MSF	NA	Brine recirculation
Ras Abu Fontas A2	36	MSF	2015	Brine recirculation
Ras Abu Fontas A3	36	RO	2017	Two passes
Ras Abu Fontas B	33	MSF	1995	Brine recirculation
Ras Abu Fontas B2	30	MSF	2008	Brine recirculation
Ras Laffan A	40	MSF	2003	Brine recirculation
Ras Laffan B	60	MSF	2006	Brine recirculation
Ras Laffan C	63	MED	2010	MED-TVC
Dukhan Plant	2	MED	1997	MED-TVC
Total	400			
Future installation				
Umm Al Houf	136.5	Combined (MSF & RO)	2018	

TVC: Thermal vapor compression.

were evaluated through LCA to elucidate environmental loads and concluded that, in the case of airborne emissions, desalination by RO with different energy systems has less of an impact than MSF and MED

[20]. The advantages of a combined cycle in a hybrid plant with integrated renewable energy production over the conventional process were presented in this paper. In the following year, the same research group assessed three commercial water production systems (MSF, MED, and RO) using LCA in part one [21], and, in part two, they compared the Ebro River Water Transfer system with the less energy-intensive desalination process, RO [22]. In part one, the assembly and operational lifecycle phases were included in the study, while the effects of chemicals and brine disposal were also not considered in this study, and the data for natural gas and electricity were based on the European “BUWAL 250” database. Three life-cycle impact assessment methods (LCIA) methods, including Eco-Indicator 99, Eco-points 97, and CML were applied with the help of the SimaPro LCA tool. In a similar conclusion to the previous study, the authors found that the operation phase of the three different technologies had a higher impact than all other life cycle phases, and the environmental impact of the RO system was the lowest (owing to its higher energy efficiency). However, part two of this study concluded similar environmental loads for both alternatives (water transfer and RO). Additionally, more detailed analyses for desalination integrated with renewable energy sources were conducted in a separate study, and showed that, under favorable climatic conditions, renewable energy sources, such as wind, solar, and hydro-power can provide substantial benefits and significantly reduce CO₂ emissions [23]. A LCA study on desalination performed in Kuwait showed several environmental impacts for both MSF and RO plants such as abiotic depletion, acidification, eutrophication, global warming, ozone layer depletion, human toxicity, marine aquatic ecotoxicity, and photochemical oxidation [24]. Variance analysis in that study confirmed that among other fossil fuel alternatives, except in abiotic depletion category natural gas generates the lowest environmental impact while crude oil generates the highest impact for global warming.

Researchers also used LCA to evaluate the environmental impacts of different potable water supply scenarios, including thermal and RO desalination. The imported water scenario was compared with three different water supply technologies for a case study in southern California using a hybrid LCA tool [25]. The results showed that the current water importation scenario had 1.5–2.4 times less environmental load than all the desalination alternatives, such as seawater and brackish groundwater desalination, along with the recycled water scenario. In a similar study based in Arizona, water importation, seawater desalination, and water reclamation were compared, and the highest impact was generated by seawater desalination [26]. Life cycle analysis was conducted using SimaPro 7.1.0 and the impact assessment method Eco-Indicator 99. The infrastructure of the water facilities was considered, and the analysis of the results demonstrated that water reclamation is the best option owing to its lower impacts, while the energy-intensive seawater desalination had the highest environmental burden.

Again in a potable water supply study, LCA was used to identify the associated environmental loads for groundwater treatment, ultra and nanofiltration, thermal desalination, and RO [27]. The GaBi 4.2 LCA tool was used to evaluate environmental burdens with the Ecoinvent database and IMPACT 2002+ as an impact assessment method. Analysis of energy and chemical consumption demonstrated that desalination processes are more energy-intensive and require more chemicals than conventional ground and surface water treatment processes, thus causing greater environmental impacts. Energy consumption has been identified as the highest contributor to the overall impacts. Hence, the study recommended a mitigation strategy of using a sustainable electricity source instead of a conventional one. Similarly, for future capacity expansion, the existing water supply scenario in Amsterdam was evaluated and compared with two alternative RO desalination scenarios by life cycle analysis [28]. LCA was conducted using the LCAqua 2.0 tool and adopting the Eco-indicator 95 impact assessment approach. The application of RO in two alternative systems resulted in higher eco-points than the existing scheme, indicating that more impacts are

generated by RO. Over half of the total impact was the result of using conventional energy sources.

There is limited research that considers the aquatic eco-toxic potential (aquatic ETP) of brine discharge in desalination-based LCA studies. Zhou et al. [19] attempted to develop an improved approach for assessing the aquatic ecotoxic potential (ETP) of brine disposal. They highlighted the benefits of a proposed group-by-group approach over the existing, commonly used approaches including the chemical-specific and whole effluent approaches. In a different study, the same research group reviewed over 30 desalination studies and identified two key issues in desalination LCA that require further improvement: feasibility and reliability [29].

1.3. Purpose of the study

Although desalination is a mature technology in Middle Eastern and North African countries, the environmental impact of this water production is poorly understood in these regions. Particularly in the case of Qatar, the environmental assessment has not been addressed comprehensively although approximately 99% municipal water demand is supplied by desalination.

The immediate critical challenge for Qatar is to sustainably produce a sufficient amount of fresh water. To achieve Qatar's national vision for 2030, focusing on the overall environmental development while achieving water security is imperative, therefore, environmental assessment of the desalination process is the key to the foundation of national strategy. As MSF desalination is widespread in Qatar, along with plans to establish more MSF plants to meet future freshwater demands, a complete environmental impact assessment of this process for this region is required. Hence, the purpose of this study is to elucidate the related environmental impacts of the multi-stage flash desalination technique when producing 1 m³ of freshwater and compare the results with other available data to justify differences in the results for different regions. Also, this study aimed to examine different scenarios for MSF desalination integrated with renewable energy for possible environmental impact reduction.

This LCA study examined the environmental loads of several MSF plants with variable gain ratios in Qatar. The application of LCA to desalted potable water production through MSF process provides a comprehensive, quantitative environmental analysis for water authorities in Qatar. This study has particular importance at a regional level as it provides a baseline for decision makers to evaluate and determine the environmental impacts and mitigation potential for future water desalination technologies for all the countries in Gulf region relying on MSF desalination technology.

2. Methodology

The LCA approach was followed in this study to examine the environmental burden associated with MSF. This approach provides the opportunity to identify the impacts of each specific stage of the desalination process, including energy intake, chemical use, and the distillation process itself. Fig. 2 illustrates the general MSF system, while Fig. 4 presents the system boundaries for environmental load analysis.

2.1. Description of the analyzed MSF plant

During MSF distillation, seawater is heated to at least 100 °C using steam under high pressure (2–3 bar), and it is then moved through a series of chambers with gradually reducing pressures. When the hot seawater enters a low-pressure chamber, it flashes and forms freshwater vapor. This vapor condenses by transferring its energy to the incoming seawater feed. The remaining salt water (called brine) enters the next chamber with a lower pressure, and the same evaporation and condensation process occurs. The remaining concentrated brine leaves the final chamber as a waste stream that is rejected back into the sea with

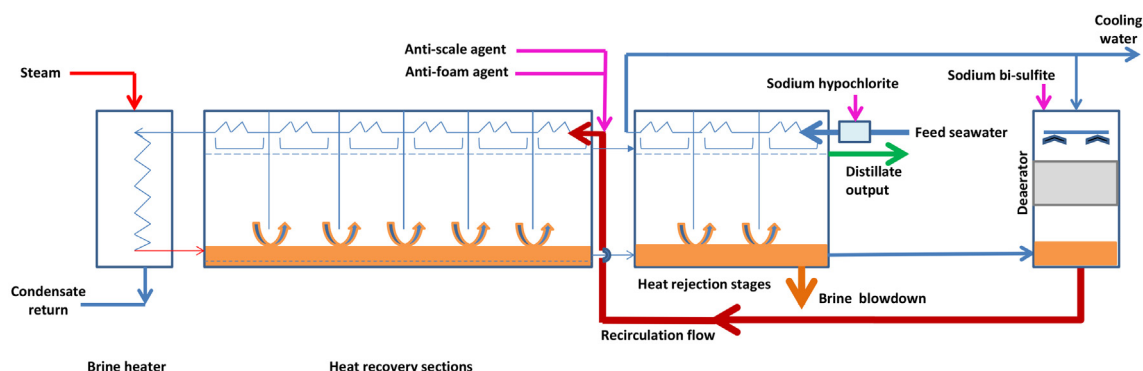


Fig. 2. Schematic of a general multi-stage flash distillation technique.

the cooling water stream, ultimately reducing the high salinity of brine stream. This technology requires high thermal energy to evaporate the saline water (the typical thermal energy consumption is 270 kJ/kg at a saturation temperature of 120 °C, while the electric pumping energy consumption is 4 kWh/m³ (14.4 kJ/kg) [30]. The performance of a MSF plant is characterized by the gain output ratio (GOR). This is the mass ratio of the distillate to the consumed steam and represents the thermal energy consumption (or fuel consumption) of the plant. The GOR also reflects the number of flashing chambers (or stages). A large number of stages would increase the GOR as more heat is recovered. Typically, the gain ratio varies from 6 to 10 for thermal processes. For most countries in the Arabian Gulf, recirculation multi-stage flash distillation (R-MSF) is the most common technique. All the analyzed desalination plants in this study are combined with natural gas turbine combined cycle (GTCC) power plant where they utilize the steam from back pressure steam turbine. This operating condition drastically reduces the equivalent fuel consumption.

This study examines three different MSF configurations, each with a different GOR. Visual design and simulation (VDS) software was utilized to create different scenarios based on Qatar's real desalination plant conditions. This program acts as platform to design and simulate various kinds of desalination plants. Process design calculations in VDS are based on specific conditions such as temperature and pressure of steam, flow rates, number of stages and others [31]. More information regarding VDS can be found in the paper by Nafey A. S. et al. [32]. Plants 1 and 2 have the conventional R-MSF configuration shown in Fig. 2, while plant 3 is an advanced pilot plant modified to increase its efficiency (Fig. 3) [31,33,48]. All the information regarding plant 2 presented here was collected through personal communication. The energy production for desalination plants in Qatar is completely

dependent on natural gas. As all the desalination plants are connected with GTCC power plants, steam from the power plant's low-pressure turbine delivers the heat to the brine heater. So, ultimately there is a work loss for power plants while supplying the heat to the MSF desalination plants. Considering this fact and the overall efficiency which is 0.48 (including the equivalent work of desalting), the consumption of fuel for desalting 1m³ of water equals to 127, 107, and 64 MJ for plant 1, 2, and 3 respectively [34]. The specifications of the three plants are summarized in Table 2.

In plant 3, distillate productivity by the MSF has been increased by increasing the GOR and top brine temperature (TBT). Generally, MSF units operate at a maximum TBT of 112 °C to avoid scale formation by different salts, such as CaCO₃, CaSO₄, and Mg(OH)₂ [35]. In the modified version, the TBT was increased by removing hard scale forming ions by a nano-filtration (NF) unit in the first stage. NF is renowned in the desalination industry as it enables the removal of divalent ions. The number of stages in the heat recovery unit was increased to 35 to increase the GOR, and the heat rejection unit was removed in plant 3. The intake seawater requirement is almost 3 times less compared to plant 1 and 2 as these plants (plant 1, 2) require a huge amount of cooling water for the heat rejection unit.

In this study, all plants have similar pre- and post-water treatment facilities, excluding plant 3 (additional NF with pre-treatment). Scale formation is a great concern for the operation team as it can severely affect the plant's efficiency and freshwater production. Acids (generally H₂SO₄) and different polymer blends, such as phosphonates, poly-phosphate, poly-carboxylic acid, and poly-maleic acid are used in most thermal desalination plants [34]. High-temperature anti-scalants are used in all the analyzed plants. The other conventional pre-treatment methods include de-aeration, and addition of NaHSO₄, active Cl₂, and

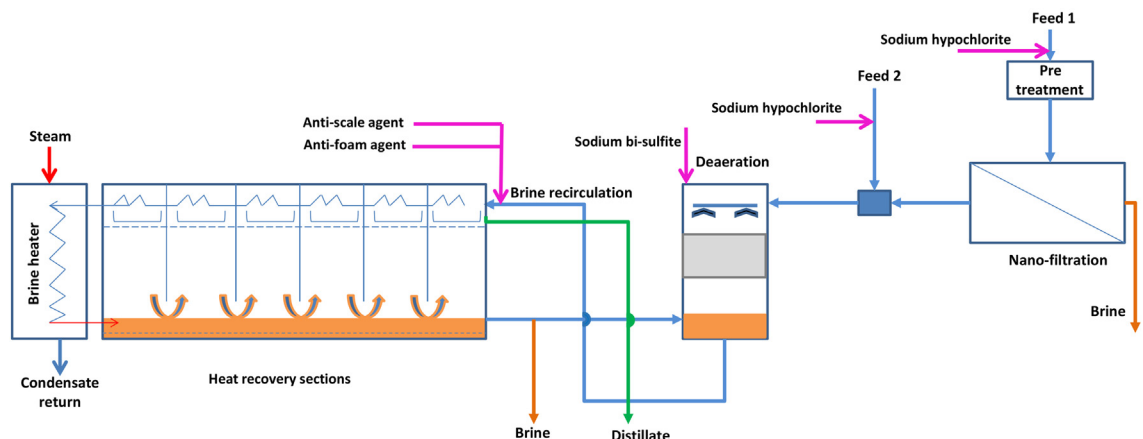


Fig. 3. Advanced multi-stage flash desalination configuration using a nano-filtration unit. The number of stages in the heat recovery unit has been increased to 35. The inclusion of additional nano-filtration pre-treatment allows the top brine temperature to reach 130 °C [31].

Table 2
Plant configuration for three different gain ratios.

Plant specifications	Plant 1 Configuration	Plant 2 Configuration	Plant 3 Configuration
Capacity (MIGD)	15	18	1.3
Gain ratio	8.21	9.73	16.07
Flow type	R-MSF	R-MSF	R-MSF
Tube configuration	Cross-tube	Cross-tube	Cross-tube
Number of stages	19	21	35
Thermal energy (MJ)	127	107	64
Mechanical energy (kWh/m ³)	4.05	4.19	3.42
Seawater flowrate (m ³ /h)	24,000	28,000	675
Distillate flowrate (m ³ /h)	2693.28	3430.57	208
Brine blowdown (m ³ /h)	5300.98	7375.26	466.49
Steam flow (t/h)	328.06	352.6	12.94

C₂H₄O to control bio-fouling and foaming. To maintain the quality of the distillate and control the growth of aquatic organisms, post-treatment is conducted in all plants using re-mineralization agents (Ca (OH)₂) and active Cl₂. Water intake in the NF unit requires some additional pre-treatment to prevent membrane fouling and improve its performance, including media filtration, coagulation, ozonation, bio-filtration, and activated carbon adsorption [36]. For our case study, chlorination, coagulation, and media filtration followed by cartridge filtration were employed as a pre-treatment method for the NF system.

2.2. LCA model framework

The continuously increasing lifestyle standards and demand for more products are resulting in stress on the natural environment. LCA is a systemic tool that quantifies the environmental impacts associated with any product or process throughout its lifespan, beginning at the initial stage (raw material acquisition) to the final disposal and helps in the selection of the least harmful product over other alternatives. The LCA tool GaBi was used to set the model framework for our study [37]. Four steps, namely, goal and scope definition, life cycle inventory analysis (LCI), life cycle impact assessment (LCIA), and the interpretation phase, act as the LCA model framework according to ISO 14040 (International Organization for Standardization) [38]. In this section, these steps are briefly discussed to describe the LCA procedure for assessing the considered MSF desalination plants.

2.2.1. Goal and scope

The first step, goal and scope definition, provides the details and intended use of the study, including the system boundary and functional unit. The goal of this study was to comprehensively quantify the life cycle impacts of desalinated water production by a MSF plant using the ReCiPe assessment method for three different scenarios: plants 1, 2, and 3 with gain ratios of 8.21, 9.73, and 16.07, respectively [39]. The functional unit for this assessment was 1 m³ of high-quality potable water at each plant so that the scenarios were comparable, while the selected scope was the gate to gate approach. The chemical and energy production for desalination and operational phases were included in the system boundary (Fig. 4) of each desalination plant. The system scope does not encompass the construction and dismantling phases as the environmental impacts of these phases are negligible compared to those of the production and operational phases according to some literatures [40,41]. Also, the water delivery from desalination plants was excluded. The temperature of the feed seawater was 35 °C for each plant. In accordance with the site specifications, some initial assumptions and limitations were as follows:

- The quality of the final treated distillate is compatible with the requirements of Qatar's Water Authority.
- The brine disposal stage was not considered here because of the following reasons: 1) majority of the MSF LCA studies have not include the brine disposal as the currently available LCIA methods are

unable to translate the concentration of salt ions present in brine into relevant eco-toxic impact. Therefore, these studies assumed that the discharged brine posed minor impact as it was fully diluted before discharging into water bodies [20,23,24,42], 2) in published literatures, MSF brine composition has not been reported completely compared to brine from RO while it requires extensive dataset for brine assessment [19].

- Pre- and post-treatment chemicals were imported from Europe, with an average ocean transport distance of 5000 km.

2.2.2. Life cycle inventory

The life cycle inventory (LCI) analysis phase aims to compile all the input and output data related to the securitized system (for our three MSF processes). Among the three different LCI methods, process-LCI covers the specific details of energy and material flows entering and exiting the system and is the main driver of this study. For system modeling, primary LCI data for all three plants were generated using VDS software and a local GaBi database (specifically for energy data input for Qatar) [31,33,37]. The input flows for three plants are listed above in Table 2. The chemical consumption for pre- and post-treatment and dosing rates are validated and are comparable to Qatar's actual desalination units (Table 3).

2.2.3. Life cycle impact assessment

The LCIA phase mainly converts the LCI data into potential environmental impacts for the product in a quantitative figure by means of characterization factors. Five main processes are included in the LCIA step: selection, classification, characterization, normalization, and weighting. ReCiPe comprises two different sets of impact categories, from which eighteen are included in midpoint impact categories, while the remaining three follow endpoint categories. An overview of the selected midpoint impact categories is listed in Table 4.

3. Results and discussion

The LCA outcomes for three different MSF plants are analyzed and compared in the following sections. Processes with higher environmental burdens for each plant were identified in contribution analysis, and all the plants were then compared. The emissions into the atmosphere produced during the desalination life-cycle (natural resources consumption, desalination operation, chemical consumption and so on) from the three MSF plants are listed in Table 5.

Generally, the MSF process releases over a hundred pollutants to the surrounding environment over its life-cycle, and the common pollutants selected for this study were CO₂, NO_x, SO₂, non-methane volatile organic compounds (NMVOC), and particulates (different sized dust particles). These pollutants were selected to compare the results with those in published literature. Analyzing the results presented in Table 5 indicates that plant 1 (with the lowest GOR and thereby highest energy consumption) exhibited the highest airborne emissions in all categories, while the modified MSF (plant 3) exhibited the lowest. The higher the

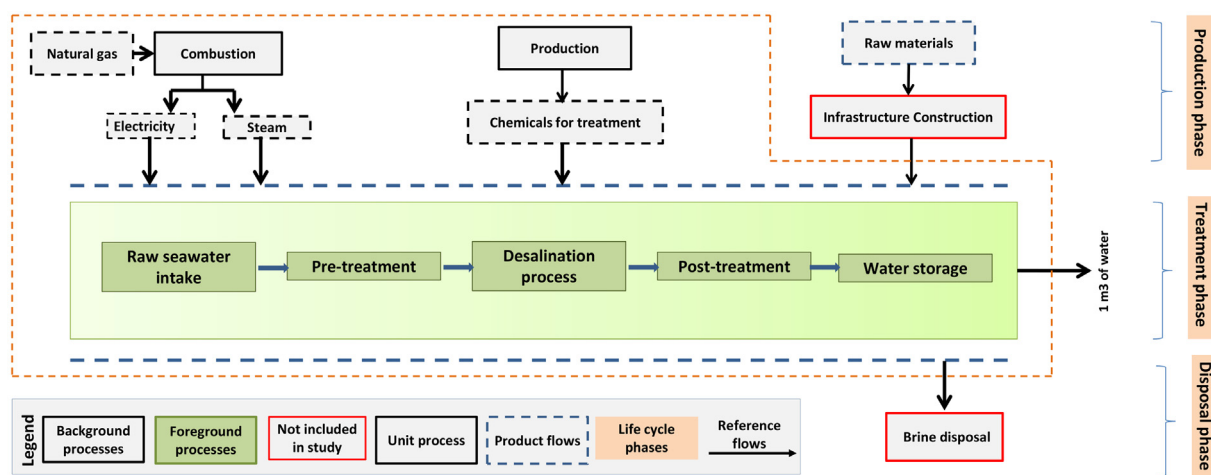


Fig. 4. System boundary for each desalination plant considered in this study. Three life cycle phases are displayed here to portray the full scenario for a MSF desalination plant, although construction in the production phase and brine disposal in the disposal phase were not considered in the LCA in this study.

GOR of a MSF plant, the more the number of stages, and hence the more will the generated vapor be reused for preheating the feedwater. This results in lower external heat requirements (in the brine heater) and hence lower fuel consumed. As a result, the energy-associated impacts of MSF reduce as the GOR increases. Thus, having the highest GOR, plant 3 consumes the least thermal energy and thereby emitting lowest pollutants into the surrounding air. So, in other words, doubling the GOR from plant 1 to plant 3 (8.21 to 16.07) has reduced the energy consumption per unit and therefore, the carbon footprint reduced by almost half for plant 3. Thus, there should be more research devoted in the direction of increasing the energy efficiency of MSF plants and exploring ways to operate them at a high TBT. This will ultimately reduce the environmental load without terminating the MSF desalination completely.

While cross validating these results with the literature, it was found that all the analyzed MSF plants in Qatar have lower air emissions than the study result presented in Raluy et al. [21]. The aforementioned study considered a MSF plant powered by steam generated from a fossil

fuel boiler directly and this results in higher thermal energy consumption (333 MJ/m^3 for MSF). Commercial desalination plants in Qatar are always operated in cogeneration mode by utilizing low pressure steam from GTCC and this results in less equivalent fuel consumption. Analyses of plants 1, 2, and 3 revealed CO_2 emissions that were 46.2%, 52.6%, and 68.7% lower than the reported value in the literature ($23.41 \text{ kg CO}_2/\text{m}^3$), respectively. Our results also differ because of the grid mix in Qatar which is 100% natural gas based, while the European electricity production mix, used in Raluy's study, consists of coal (43%), nuclear (40%), and hydropower (17%). It should be also noted that, sea water quality and scope of the studies were not identical for two cases.

In spite of having these relatively lower values, Qatar is producing huge quantity of desalinated water annually. According to the latest available information, the total desalinated water production was $493.20 \text{ million m}^3$ in the year 2014 [4]. As per the technology share, 75% of desalinated water or around 370 million m^3 water is produced using MSF technology. Hence, the annual water production through

Table 3

Pre- and post-treatment chemicals for plants 1, 2 and 3.

Stage	Systems	Dose rate (ppm)	Comments
Pre-treatment for plants 1, 2, and 3	Chlorination	4	Intake feed water contains various bacteria, micro-organisms, and protozoa. To control biological growth in the desalination plants, cost-effective chlorination is used. Typically, active chlorine or sodium hypochlorite are added for chlorination; sodium hypochlorite was added in this study.
	Deaeration	0.5	Sodium bisulfite is used to control corrosion by removing dissolved gases.
	Anti-scaling	2.4	Scaling is a common phenomenon in desalination, especially for thermal distillation with a high TBT. Scaling is generally prevented by adding acids or polymers, but acid treatment is rarely used. In this case, due to data constraints, sulfuric acid was used as an antiscalant in GaBi.
	Anti-foaming	0.1	To reduce the foaming action by polyethylene oxide, monoethylene oxide was considered in the LCA due to data constraints.
Post-treatment for plants 1, 2, and 3	Re-mineralization	0.5	Desalination processes produce a final distillate with poor mineral content and a high potential for corrosion, and, most significantly, an adverse effect on human health. Calcium hydroxide was used in each case.
Pre-treatment for NF system (plant 3)	Disinfection	0.5	Sodium hypochlorite, as a form of chlorination, was used for disinfection in this case study.
	Coagulation	0.3	Coagulant aids are used to alter the particle charge, which helps to combine small particles into aggregates for an easy settling process. Different poly-electrolytes, ferric salts, alums, and lime are added for coagulation in NF pre-treatment. Ferric chloride was injected in the studied process.
	Granular media filtration	0.6–1 mm	Act as a sedimentation basin. Double stage filtration was designed to remove coarse solids in the plants.
	Chlorination	2	To prevent bio-activity in the NF membrane, chlorine must be added. In the summer, the optimum dose is 2 ppm, while this can be reduced in the winter.
	Cartridge filtration	10 μm	To ensure no passage of particulates in the NF passage area.

Electricity production data for Qatar was obtained from the GaBi local database. The transmission losses were included in the calculation and production of electricity.

Table 4
Overview of midpoint impact categories in ReCiPe [43].

Impact categories	Abbreviation	Units	Indicator name
Climate change	CC	kg CO ₂ -Equiv.	Infra-red radiative forcing
Ozone depletion	OD	kg CFC-11 eq.	Stratospheric ozone concentration
Marine eutrophication	ME	kg N-Equiv.	Nitrogen concentration
Human toxicity	HT	kg 1,4-DB eq.	Hazard-weighted dose
Fossil resource depletion	FD	kg oil eq.	Upper heating value

Table 5
Detailed data for emissions into the atmosphere for plants 1, 2, and 3.

Emissions	units	Plant 1	Plant 2	Plant 3
Carbon dioxide	kg/m ³ of desalted water	12.6	11.1	7.32
Nitrogen oxides	g/m ³ of desalted water	16.4	15.1	10.9
Sulfur dioxide	g/m ³ of desalted water	2.13	1.86	1.29
Group NMVOC	g/m ³ of desalted water	2.77	2.43	1.56
Particulates to air	g/m ³ of desalted water	0.378	0.34	0.213

NMVOC: Non-methane volatile organic compounds.

MSF releases approximately 4.66 million tons of CO₂ which have both short- and long-term adverse effects on human health and the environment. Modification of the existing MSF plants according to plant 3 specification has the potential to cut down CO₂ emissions to 2.7 million tons annually.

3.1. Contribution analysis

The production of freshwater through MSF distillation comprises several processes that all contribute to the overall environmental burden. Identifying the contributions of different processes associated with MSF desalination enables us to identify the dominant steps or materials in the whole system. Therefore, for further investigation, all the analyzed MSF techniques were divided into four sub-processes: 1. use of thermal energy, 2. use of mechanical energy, 3. chemical use in pre-treatment, and 4. chemical use in post-treatment. The contribution of each sub-process in the three plants to five different impact categories are shown in Fig. 5.

The LCA results showed that the highest impact is due to the use of

energy in distillation, while the use of chemicals in pre- and post-treatment has a very minimal impact in all categories, excluding the ozone depletion category. The characterization factor of ozone depletion considers the damage to the stratospheric ozone layer by recalcitrant chemicals based on either chlorine or bromine atoms. Both pre- and post-treatment chemicals contain chlorine substances for controlling biological growth, especially those used in pre-treatment, which requires a higher dose of chlorination than post-treatment. Fig. 5 clearly shows a higher percentage of impact from pre-treatment chemicals, as compared to post-treatment, in the ozone depletion category for all three plants. As it is widely used in other impact assessment methods, global warming potential is the selected characterization factor for climate change category. This characterization factor takes account the infrared radiative forcing increase of greenhouse gas. All the plants exhibit the same dominating scenario for thermal energy use in desalting process in this impact category, indicating the significant emission of CO₂-Equiv. Fossil fuel combustion and the release of heated effluents to water creates favorable conditions for marine eutrophication, as shown in marine eutrophication category. Similarly, the effects of fossil depletion due to natural gas (NG) usage in the production of steam and the toxicity effect of chemicals on the human food chain are represented in both fossil depletion and human toxicity categories, respectively.

From Fig. 5, it is clear that plant 1 has the highest impact, while plant 3 has the least. The major environmental impacts of plants 1, 2, and 3 are caused by the use of thermal energy in MSF desalination. The consumption of electrical energy for pumping exhibited similar environmental impact values. As previously discussed, we can strongly deduce that a change in GOR caused a significant difference in the impacts generated from the amount of thermal energy used to produce

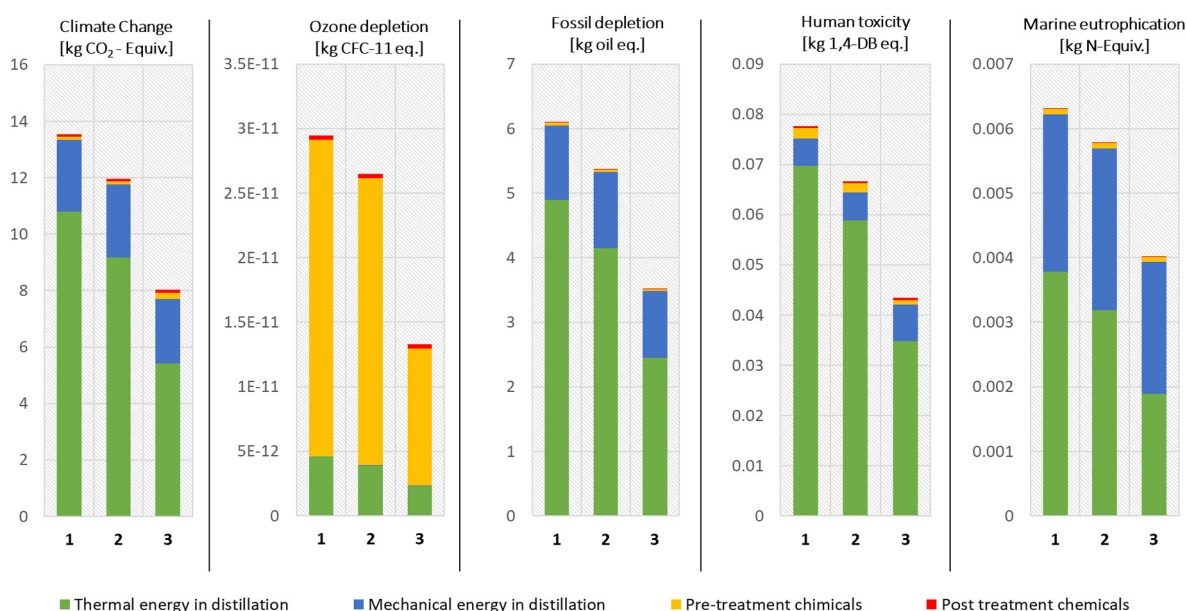


Fig. 5. Impact results of five categories for each MSF desalination plant. The number 1, 2, and 3 in the above figure indicates the three MSF plants: plant 1, Plant2, and plant 3 respectively. The description of the plants is as follows: gain ratio of plant 1: 8.21, gain ratio of plant 2: 9.73, gain ratio of plant 3: 16.07.

1 m³ of fresh water. The plant with the lowest GOR (plant 1) posed the highest impacts due to a smaller number of stages and hence, recovery while the advanced MSF configuration presented lower impacts as the GOR was increased to 16. Although the modifications of plant 3 added cost due to the increase in number of heat recovery stages and additional nano-filtration pre-treatment, the significant decrease in thermal energy use decreased the operational costs, ultimately resulting in lower environmental impacts than the conventional system.

3.2. Scenario analysis: hybridization with solar thermal energy

Using solar energy to power MSF opens the possibility of reducing the energy associated environmental impacts [44]. Because of the abundant solar resources available in Middle Eastern countries, it is highly suitable to replace the conventional energy sources to some extent in the State of Qatar. This study aimed to examine the scenarios for MSF desalination coupled with renewable energy by introducing different percentages of solar thermal energy (5%, 10%, 15%, and 20%) in the system boundary to supply a part of the required steam to the desalination unit. In these three scenarios, we assumed that a concentrated solar power (CSP) plant is supplying a fraction of the MSF plant's required thermal energy. The construction of the solar power plant was excluded from the boundary as it has a minimal impact (6.5% of the life cycle emissions for a wet-cooled system) [45]. The major outcomes from the scenario analysis for three MSF plants are shown in Fig. 6.

The similar decreasing trend of CO₂ emission has been observed for all the three MSF plants with the least possible CO₂ emission being 6.31 kg/m³ for the advanced MSF plant with highest GOR. It was found that, for plant 3, supplying 20% of the thermal energy demand from solar energy reduces the CO₂ emissions by 13%. Though the inclusion of the solar field construction can raise the emission to some extent, still this result provides a considerable alternative for fossil fuel usage in terms of environmental impact reduction.

3.3. Data quality and uncertainty

LCA studies have uncertainties due to several reasons which have been discussed here for this case study:

1. The primary data collected for this study is mainly based on a software model where few data can be inaccurate or do not represent the real plant scenarios.
2. The seasonal variation (e.g. change in inlet seawater temperature or

quality of feed water) is not considered in this study which can be a source of uncertainty.

3. Generic chemicals have been used in the case of anti-scale and anti-foaming agent as the real chemical formula is a secret for every desalination industry.

4. Conclusions

In this study, the environmental impacts of conventional MSF plants operating in Qatar's desalination industry were examined and compared to an advanced MSF configuration using the LCA software, GaBi, by Thinkstep. Although this study had some limitations and assumptions, the results are significant to Qatar's water authority as to the best of our knowledge this study is the first attempt here to quantify the environmental burdens associated with the water production system through LCA. As the MSF process produces most of the potable water in Qatar, this study has the potential to act as a baseline for policymaking in the water sector. Also, the quantitative results are highly important for increasing the awareness among general people in Qatar for reducing the daily life water misuse.

For all impact categories, the advanced MSF-NF plant exhibited significantly lower impacts than the conventional configurations, which demonstrates the possibility of improving the efficiency of MSF technologies with a great reduction in environmental impacts. As Qatar's water authority is planning to increase the desalination capacity in the near future to meet the continuously increasing water demand, this modified plant could become the solution to Qatar's water problem while helping to achieve Qatar's National Vision 2030 by reducing overall environmental impacts.

The general conclusions of this study are listed below:

1. Thermal energy use in desalination process has the overall highest contribution to environmental impacts. Impact analysis indicates the highest percentage impact in human toxicity category followed by climate change, fossil depletion, marine eutrophication, and ozone depletion categories due to use of thermal energy in desalination process.
2. There is a high potential to reduce the impact of MSF desalination by increasing the GOR through advanced feedwater pretreatment using NF.
3. Due to energy limitation, many countries around the world have already started extensive research and application of renewable energies in water sector. Even though the gulf countries are rich in energy, they are also shifting to the same trends. For example, study

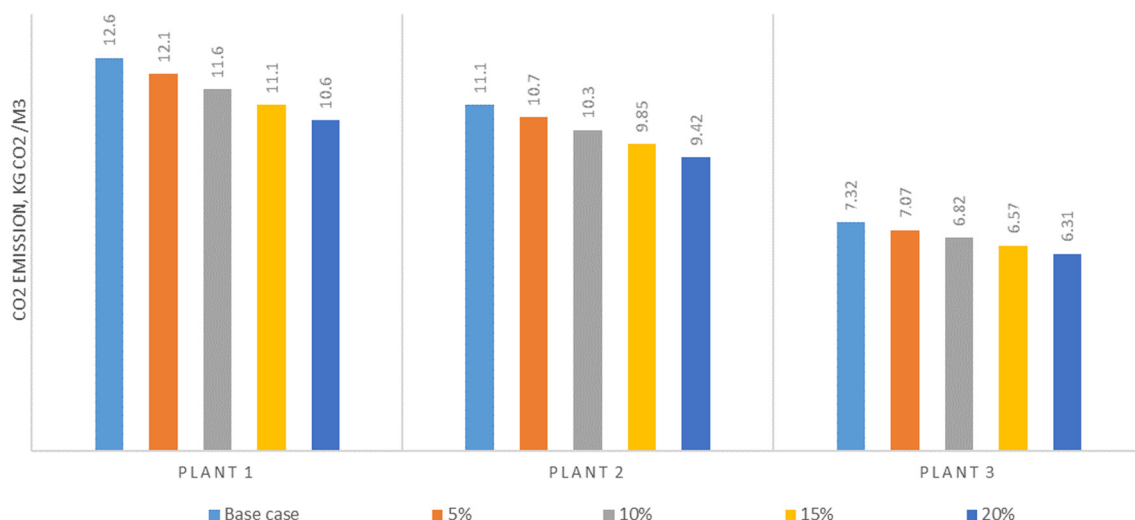


Fig. 6. Reduction in CO₂ emission as a result of integrating solar thermal energy. Four different scenarios (coupling of 5%, 10%, 15%, and 20% of solar thermal energy) have been examined and compared with the base case results for three MSF plants.

in the UAE successfully investigated the design and feasibility of using parabolic trough collectors and solar ponds to meet the complete energy requirement for MSF desalination [46].

In near future, Qatar should consider utilizing available renewable energies for desalination. Therefore, the scenario analysis provides the preliminary assessment results to the policy makers indicating the possible CO₂ reduction amounts. Hence, this study opens more door for future research on implementing solar thermal energy more effectively coupled with MSF desalination. This future research area can reveal more sustainable solutions for achieving water security in Qatar with minimal impacts on the environment.

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